SIM System Testbed III

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ABSTRACT

The System Testbed III (STB-3) is the flagship testbed in JPL's Interferometry Technology Program for the Space Interferometry Mission, in which it holds a place as the piece of ground hardware that looks and acts most like the real SIM space system.

STB-3 is a 3-year, $11.2M program targeted at demonstrating that the SIM architecture, using two interferometers trained at bright guide stars to stabilize a third "science" interferometer in pathlength and angle, will work. STB-3 will also demonstrate much of the complexity of full SIM operations in the laboratory by the end of 2001.

STB-3 is currently operating on optical tables in its first phase and is in the process of being moved to a full-size flight-like structure where feedforward stabilization of the science interferometer will be re-demonstrated. Finally, in its third phase, STB-3 will add autoalignment and other autonomous operations.

This paper will present the current status of and data from STB-3, what's been learned about feedforward stabilization, and designs and plans for phases 2 and 3.

Keywords: SIM space interferometry pathlength feedforward angle technology control

1. INTRODUCTION

NASA's Space Interferometry Mission seeks to improve the state of the art in the measurement of star positions by orders of magnitude. A natural impact of this goal is that the development of the SIM instrument and spacecraft push the state of the art in a number of key technology areas, including distance measurement, thermal measurement and control, optical materials and figures, and vibration control.

In order to address these technology drivers, several testbeds have been developed through the Jet Propulsion Laboratory's Interferometry Technology Program. Within the technology program, the SIM system testbed III (STB-3) is being developed to bear a maximum resemblance to SIM, in order to accurately reflect its dynamic behavior, thus validating that controls approaches developed on STB-3 will port smoothly to SIM.

Unlike SIM, however, STB-3 operates in an air-filled laboratory and must demonstrate SIM performance objectives in the presence of acoustic, thermal, and ground-vibration effects whose tendency is to drown out the performance parameters that we're trying to measure. So a big part of the STB-3 development approach has to do with dealing with these issues of validating SIM's on-orbit performance using a testbed in an air-filled laboratory.

The STB-3 testbed and the SIM spacecraft are shown side-by-side in the Figure 1. The STB-3 testbed has now been modified slightly from this original diagram; an updated version is presented later, but this figure is more illustrative for comparison purposes.

Comparisons show a few differences between the two. STB-3 does not have solar panels or other spacecraft functions, although it does contain a "backpack" mounted beneath the test article, which contains a reaction wheel and isolators and which represents the spacecraft system to which the interferometer instrument is attached. STB-3 mounts its optical components on top of the structure, rather than inside, for ease of access and simplicity of design, in order to help keep costs

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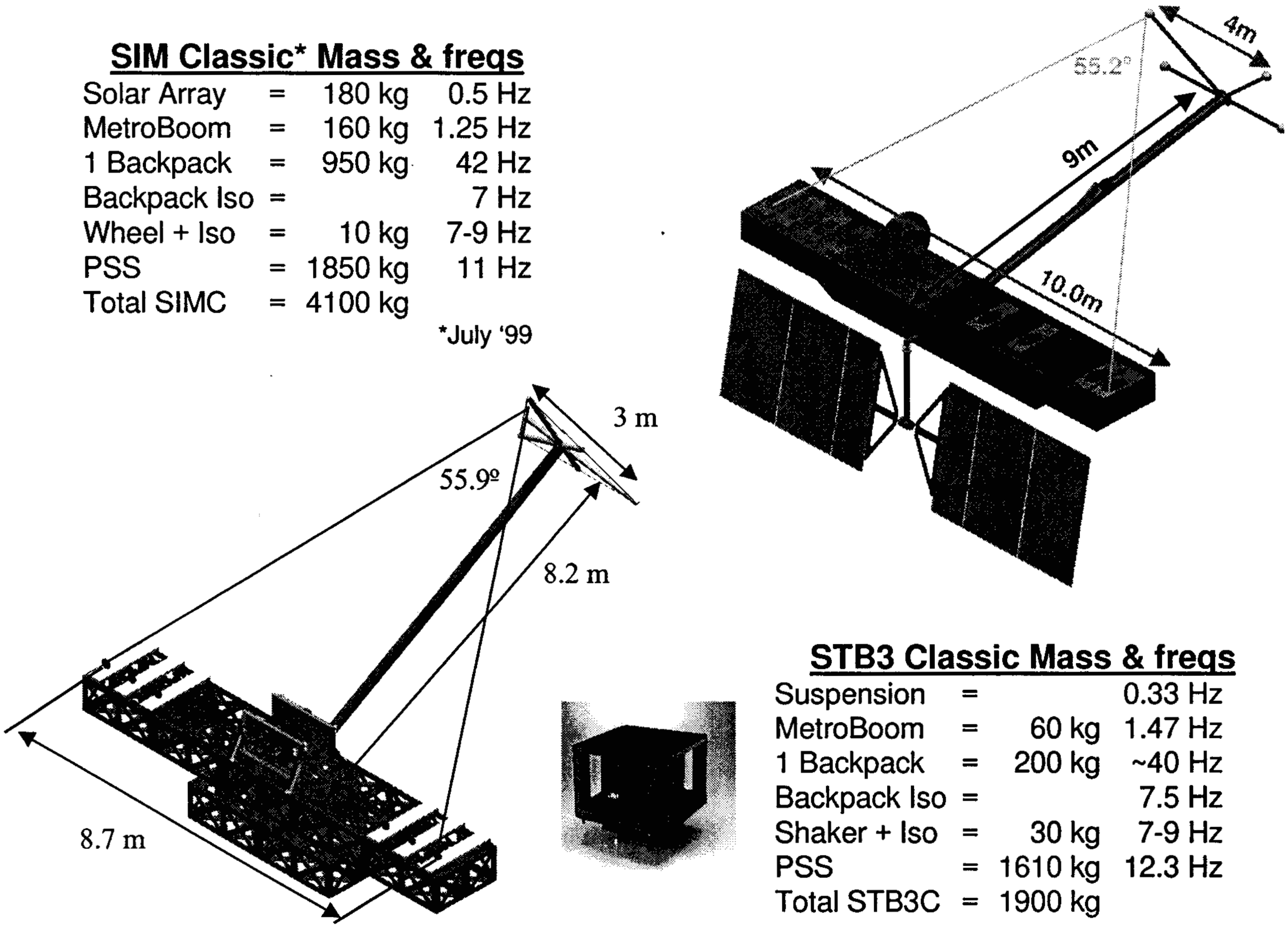


Figure 1. The STB-3 testbed (left) and the SIM spacecraft (right). The long protrusions are the external metrology booms.

down. SIM includes redundant hardware (eight siderostat bays shown in this picture), which STB-3 does not. The apparent difference at the end of the metrology boom (three reflectors on a triangle vs. four arranged in a square) has been removed in a more recent design.

The following figure shows the STB-3 testbed as it will appear later this year when installed in its final home in a high bay laboratory at JPL. This is referred to as the "Phase 2" configuration of STB-3.

In addition to the "test article" shown in the figure, which represents SIM, STB-3 also makes use of a sophisticated star simulator which will be used to provide three incoming parallel wavefronts to the test article.

Currently, STB-3 is working through its "Phase 1" development. Phase 1 involves the assembly of the individual pieces of the STB-3 optical system on an optical bench, where the functionality of the system can be verified prior to integration on the 8.7-m structure. Phase 1 is based on an earlier, now-obsolete architecture for the SIM mission (known as Son-of-SIM, or SOS), whereas Phase 2 is based on the "SIM Classic" architecture. However, since STB-3 Phase 1 does not include an articulating wide-angle-collector system, the impact of this difference is negligible.

A photograph of the Phase 1 system is shown in Figure 3. The beam trains through the system are highlighted.

A detailed discussion of the Phase 1 and Phase 2 systems is presented later in this paper.

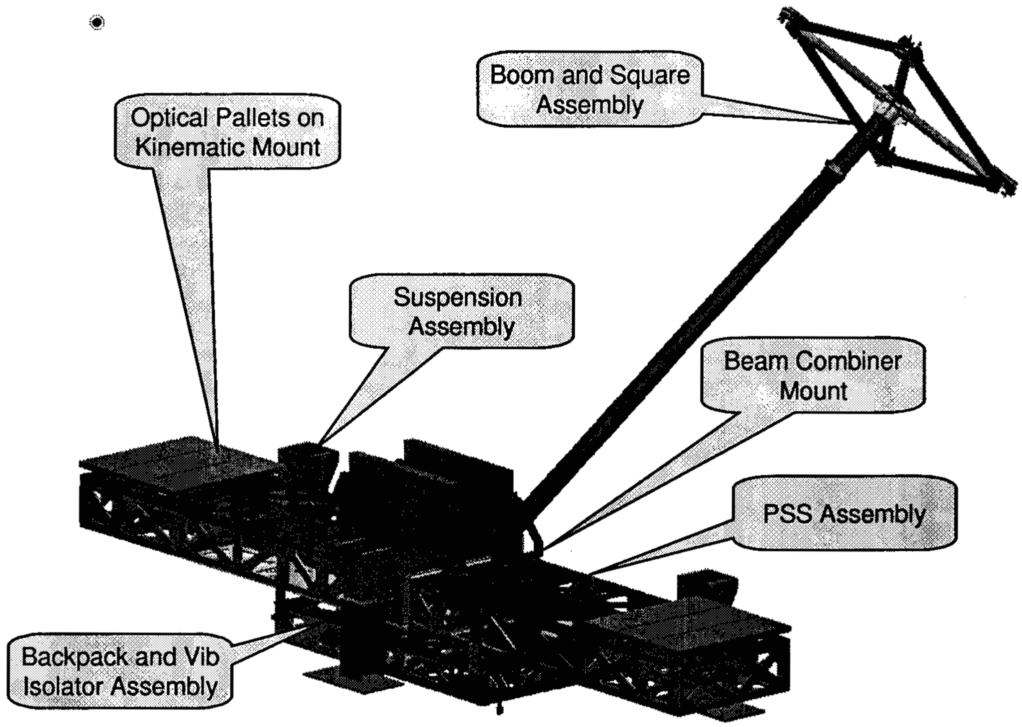


Figure 2. STB-3 Phase 2. The structure is 8.7 meters long.

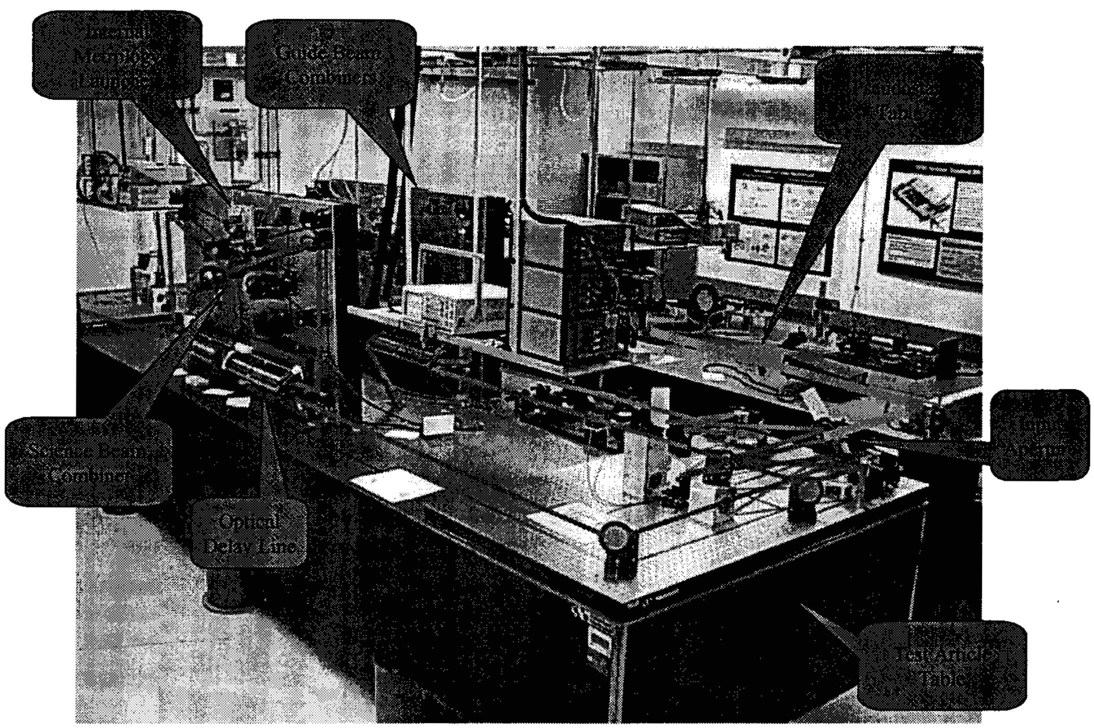


Figure 3. STB-3 Phase 1 setup. The optical table in the foreground is 5 meters long and represents a half-scale SIM. The optical table in the background is a pseudostar that produces three simulated stellar wavefronts.

STB-3 plans call for an initial demonstration of the SIM "pathlength feedforward" (PFF) function at low frequencies in the Phase 1 laboratory this summer. Installation of the structure will occur in August, with initial operations on the structure planned for September. At that point, work will begin on extending PFF results to high frequencies and on also demonstrating the stabilization of wavefront tilt. Details on these demonstrations and on the plan appear later in this paper.

2. SIM TECHNOLOGY APPROACH

The Space Interferometry Mission depends on the deployment of a number of new technologies, all of which must be successfully demonstrated prior to the commencement of the SIM Implementation Phase, currently planned to start in late 2001.

2.1. The SIM Technology Tapestry

In order to manage the development of these technologies in a cohesive way, SIM has developed a *Technology Readiness / Design Verification Matrix* (TRDV), which catalogs SIM requirements and technology needs and how they are being addressed. Some items will be proven by analysis, others will be handled by designs that will be shown to meet the requirements, and others will be proven in testbed demonstrations.

There are a broad array of testbeds in the SIM program, spread across the three SIM partners, TRW, Lockheed-Martin Missiles and Space, and the Jet Propulsion Laboratory. A few of these testbeds are called out in the table below.

Testbed	Objective
Substructure Test Article	Study joints and structure issues at the SIM picometer-nanometer distance scales
Thermal-Optical-Mechanical testbed	Sudy the behavior of SIM's optical and mechanical components over temperature (milli-Kelvin variations) at these scales
Microarcsecond Metrology testbed	Demonstrate microarcsecond astrometric performance given precision components
Nulling testbed	Demonstrate deep starlight nulls needed for planet detection
Metrology gauge testbed	Demonstrate picometer-scale distance measurement
System Testbed 3	Demonstrate controls architecture required by SIM. Reject disturbances from vibration sources and environment.

Table 1. Partial List of SIM Technology Testbeds

The SIM TRDV is broken into a number of areas, including technology and I&T. The TRDV approach takes SIM requirements in the areas of flight technology and integration and test capability and allocates them to testbeds, modeling, design, analysis, etc.

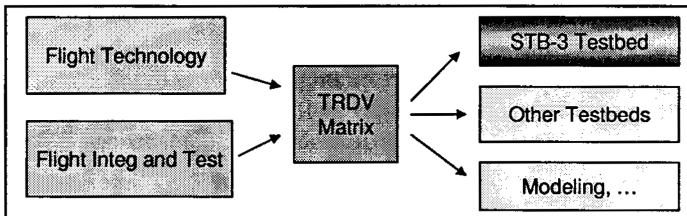


Figure 4. SIM Technology Validation Approach

2.2. STB-3 Technology Goals

STB-3 has been assigned specific TRDV items to validate. In general, STB-3's assigned technologies are in three system-level domains, Dim Star Controls Technology (pathlength & angle feed-forward in presence of structural dynamics), SIM Realtime Control Complexity Pathfinder (3-Baseline operations, Autonomy, Self-calibration, Error recovery), and Instrument System Integration and Test (Testing methodology, 3-Baseline Pseudostar, Suspension system and disturbance injection, and Electronics and software interfacing). The detailed assignments are summarized in Table 3.

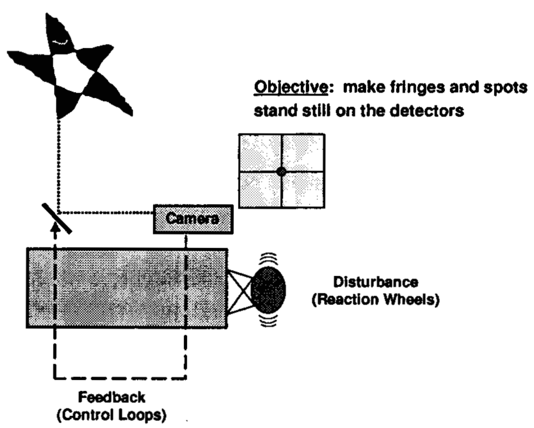
3. STABILIZATION OF DIM-STAR FRINGES

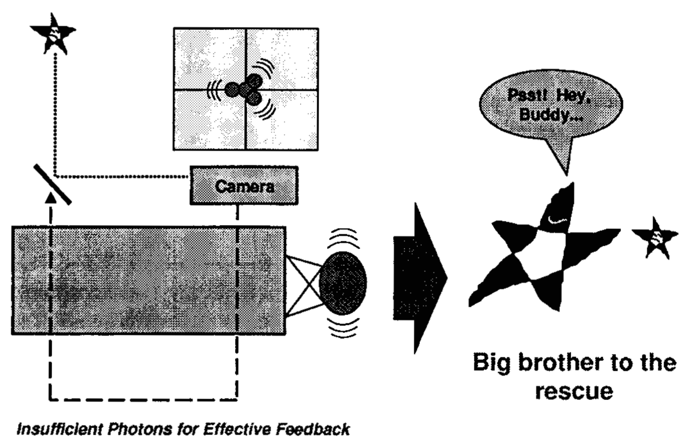
The major control objectives of STB-3 have to do with demonstrating the ability of SIM to observe very dim stars. For some targets, SIM may require integration times of an hour. It is therefore necessary on a one-hour timeframe to stabilize the internal optical paths and the wavefront tilts of the interferometer in order to be able to achieve a coherent integration. These stabilizations must be good to about 10 nm of pathlength and 1 arcsec of tilt.

3.1. The Feedforward Approach

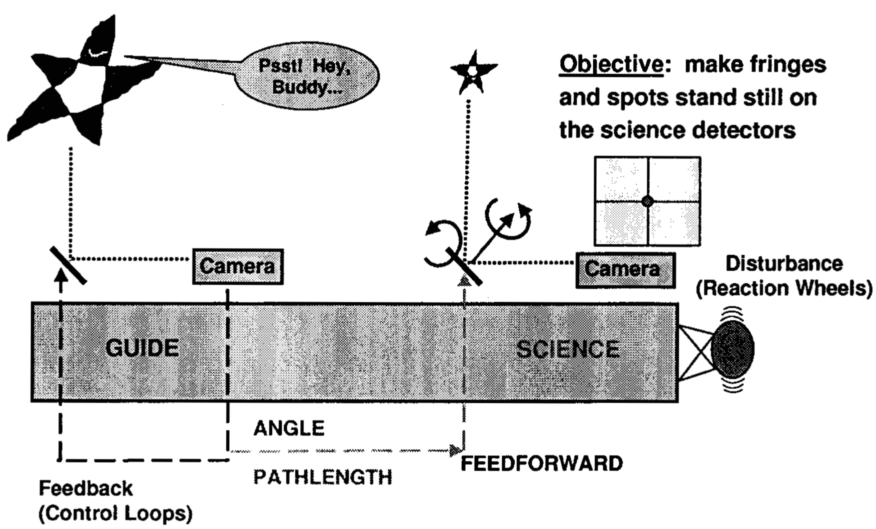
In practice, it is quite difficult to achieve this level of absolute stability, due to the vibration environment present on even the quietest spacecraft. The biggest single problem for SIM is vibrations caused by the spacecraft's reaction wheels. But, although stability at this level is impractical, it is nonetheless possible to achieve the coherent integration we desire by making corrections to the internal pathlengths and wavefront tilts in realtime.

For a bright star, this is done by simply sensing the tilt and pathlength offset of the incoming waves and making corrections using feedback, as shown in the cartoon on the left, showing a simple tilt control loop. In the cartoon on the right, however, the star is not bright enough for effective feedback, so the tilt is uncontrollable, and the image becomes blurred.





The solution, as indicated in the cartoon on the right, is to use photons from a bright star, known as a guide star, to help stabilize the wavefronts from the dim star, typically referred to as the science star, as shown here.



In practice, this technique is tractable, but it obviously requires lots of sensors. In order to provide information that accurately positions controlled optics for the dim star, it is necessary to sense not only what is happening to the bright star path, but to sense the relative motions of any optical components that the two beam trains do not have in common.

For pathlength control, this means monitoring the internal pathlength difference in each interferometer, as well as the motions of the endpoints of those internal pathlengths (i.e., the baseline). Internal paths are measured using a single laser metrology beam originating from the beam combiner for the baseline. External paths are measured by a network of metrology beams that measure the motions of the baseline endpoints with respect to a group of four retroreflectors located on the square at the end of the 8.2-meter metrology boom. The process of combining this information together with the measured fringe position from two bright-star guide interferometers, in order to produce a pathlength correction for the dim-star science interferometer, is what we refer to as pathlength feedforward.

For wavefront tilt control, the problem is somewhat tricky. Some initial test results from the MPI testbed indicate that it may not actually be necessary for SIM, that the wavefront tilts are passively stable enough. If this is not the case, the scheme proposed for SIM at the moment uses a tilt-sensing beacon that propagates through the starlight beam train measures the tilt of the dim star directly. In point of fact, although this process has been known as "angle feedforward" in SIM circles, most proposed dim-star tilt control architectures do not use feedforward. In the case proposed here, the tilt is measured directly and ordinary feedback is used.

Nonetheless, the challenge of dim-star wavefront tilt control has been laid on STB-3, and STB-3 will be implementing the SIM architecture for this about a year after this conference.

4. PROJECT APPROACH

4.1. Technical Approach

There are several aspects of the STB-3 technical approach which are critical. Probably the most important of these is performance validation. Our goal is to demonstrate that SIM will be able to achieve dim-star fringes stabilized to about 10 nm, in the presence of expected on-orbit disturbances, particularly a reaction wheel. In the lab, then, we will outfit STB-3 with a reaction wheel, and with a shaker than can provided simulated reaction wheel disturbances, possible scaled to have greater amplitude than the wheel itself would provide.

When trying to convince ourselves that a testbed in a laboratory environment validates the operation of SIM at the nanometer level, a number of issues arise. For example, with atmospheric effects on slow timescales (>10 seconds) causing measurement errors as high as 50 nm or more in our data, we clearly have to do something more sophisticated than just taking measurements and hoping the results are at the 10-nanometer level.

Our first line of defense is to do what we can to quiet the laboratory environment. This includes placing the testbed on a very soft suspension (0.3 Hz), to eliminate high-frequency coupling through the floor, and possibly doing some acoustic mitigation or adding air tubes for the beams to go through.

The second part of our approach involves using linearity and transfer functions to extrapolate performance to orbit. That is to say, if the atmospheric effects are ten times larger than we can really tolerate in order to make measurements at the accuracy we like, then we'll just shake the testbed ten times harder than a reaction wheel actually would. If the system is linear, then as long as we show the requisite level of vibration attenuation, our objective has been met.

It is important, then, for the system to be as linear as possible. Due to structural damping from cables and so on, it will probably not be realistic to assume linearity over regimes of operation with shaking hundreds of times more violent than the reaction wheel. Therefore, we will work hard to eliminate as much environmental disturbance as possible, and then use linearity just to get the last factor of a few that we need to achieve our objective.

4.1.1. Bright-star testing and the performance metric

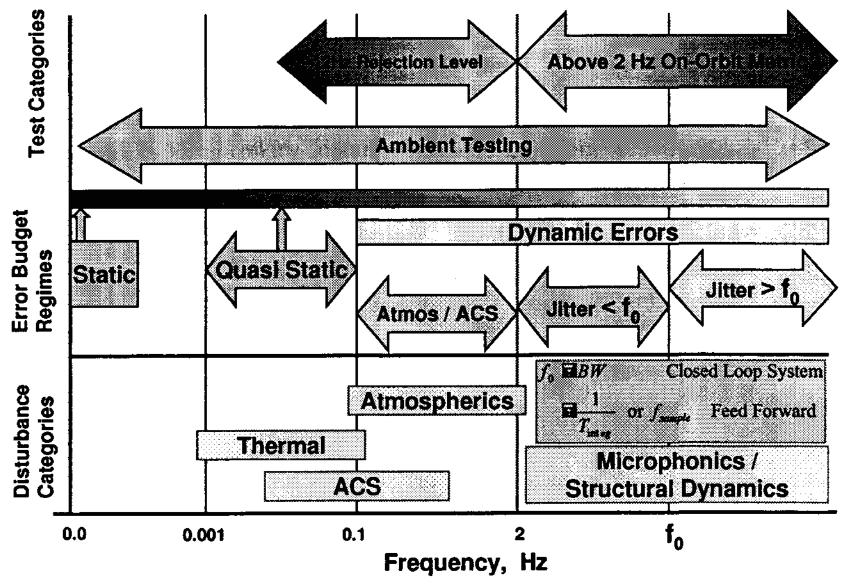
There are two ways, conceptually, that we could make the measurements we need. The most direct approach would be to actually stabilize the dim-star pathlength to 10 nm and tilt to 1 arcsec and then show that we can perform a coherent integration on the dim-star baseline. This would be accomplished by, in realtime, computing the feedforward signals to the dim-star baseline and applying them to stabilize the dim-star pathlength and tilt. However, since 10-nm stabilization may be impractical in the laboratory, the proposed approach of demonstrating coherent integration is in jeopardy.

Instead, our approach is to actually use a bright source for the "dim" star. We then measure and control the fringe motion and wavefront tilt of the "dim" star and compare it to what the feedforward signals were predicting. The difference between predicted and actual values for these quantities becomes our performance metric. That is, for example, if we can get actual and predicted pathlength variations to agree to within 10 nm rms (scaled based on the magnitude of the disturbance input with respect to the disturbance of an actual reaction wheel), then pathlength feedforward is working.

4.1.2. Frequency regimes

The problems with damping and non-linearity do not apply for frequencies where the system behaves as a rigid body. Since the first mode of the structure is around 12 Hz, disturbances below a few Hz are not affected by the linearity limitation.

For this and other reasons, it is natural to divide the STB-3 disturbance rejection problem into two regimes, the above-2-Hz regime, and the below-2-Hz regime. The "other reasons" include a transition in primary disturbance source from reaction wheels and acoustics (at high frequency) to Attitude Control System (ACS) pointing errors and atmospherics at low frequency. For this reason, we refer to the above-2-Hz regime as the "vibration regime" and the below-2-Hz regime as the "ACS regime."



STB-3, therefore, partitions our problem into four major components, consisting of Pathlength and Angle Feedforward above and below 2 Hz.

4.1.3. Initial rigid-body testing

In Phase 1, STB-3 is on optical tables while we develop and validate the functionality needed for the on-structure tests. However, we can also perform some amount of performance testing in parallel, attacking the rigid-body part of the problem, as shown in the figures below. In the figure below, STB-3 is shown moving as a rigid body due to ACS pointing errors.

Although the diagram shows this occurring for STB-3 in Phase 2 on a structure, this testing can also be performed in Phase 1 on optical tables, and this is in fact our plan. Dr. Yekta Gursel of JPL is developing an electromagnetic 6-degree-of-freedom attitude control system for use with the Phase 1 and Phase 2 versions of STB-3. Just as the shaker can be used to simulate and inject reaction wheel disturbances, Gursel's ACS can control the STB-3 test article's attitude and inject ACS error disturbances for rejection by the system.

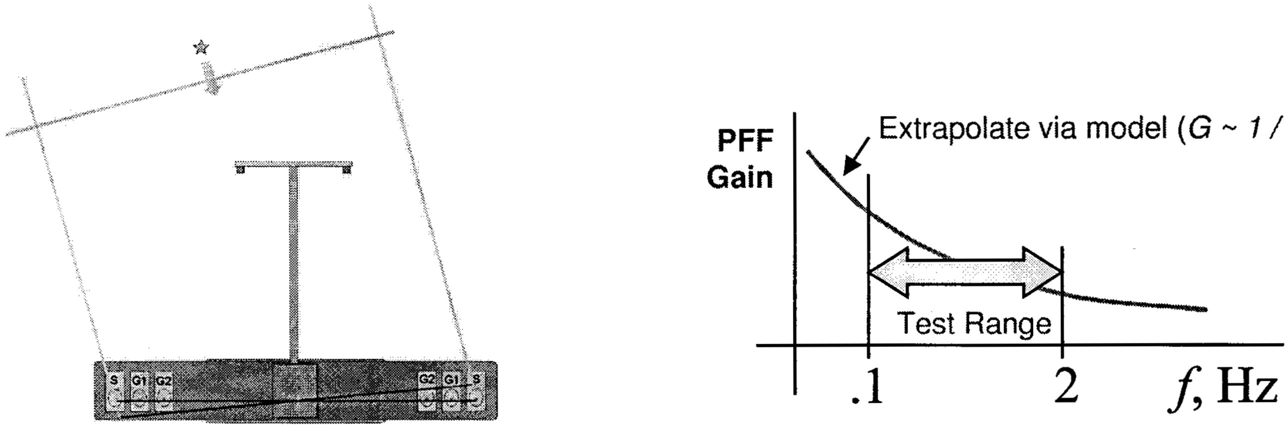
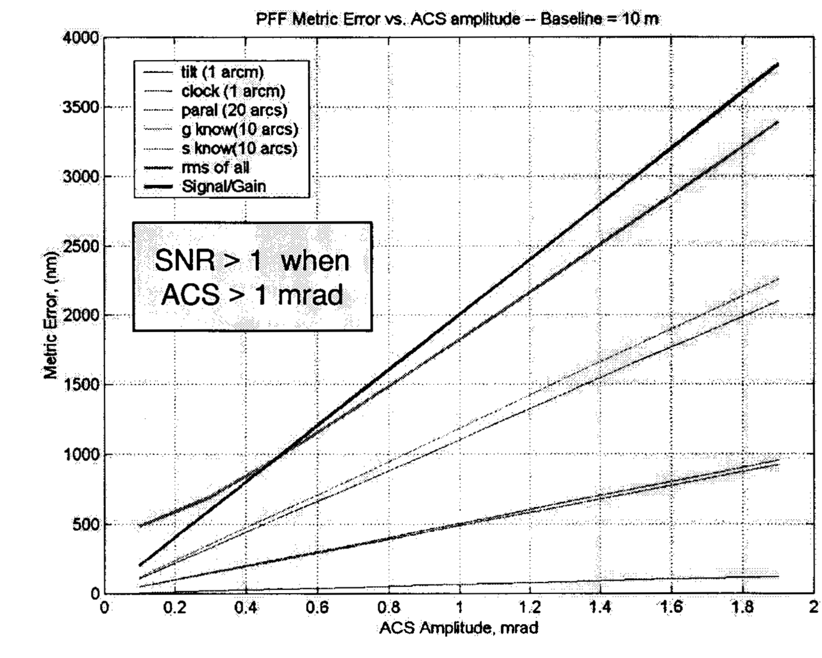


Figure . ACS motions, and the frequency regime for ACS testing.

As shown in the figure on the right, we plan to do this testing down to a frequency of about 0.1 Hz. While SIM's integration time is as long as one hour, SIM's system engineers who put together the TRDV feel that, if we can show fringe stability on a 10-second timescale, this will extrapolate to one hour, assuming good thermal control. The issue thermal control has been assigned to and is being addressed by other SIM testbeds.

One major issue when trying to perform testing in this regime is whether we can actually get a PFF signal large enough to see. The problem is that there are systematic errors in the results due to alignment and other static errors. And, unlike the errors in the vibration regime, the magnitude of these errors grows larger as you try to inject greater disturbance into the system. The question arises "Can you ever win?" The answer is yes, if a sufficiently large amplitude disturbance is provided, as shown here. In the figure, the vertical axis represents the magnitude of pathlength variation due to various effects, while the horizontal axis is the amplitude of the ACS disturbance. As you can see, at low amplitudes, the desired signal, represented by the black line, is actually smaller than the contribution due to the various error sources. However, by increasing the magnitude of the disturbance beyond 0.5 mrad the desired signal starts to poke through and eventually is larger.



It is interesting to note, however, that this effect was quite worrisome for a while, in that it places requirements on the suspension system (to allow excursions of ±2.5mm at each end of the boom (0.5 mrad over 10m)), the attitude control system (to push a 1600kg structure through ±2.5mm at 2 Hz), and the metrology system (to allow pathlength rates of change on the order of 1 cm/sec). At this point, all of these issues are resolved, and it is believed that the system will work.

Initial testing of rigid-body-regime pathlength feedforward is set to begin testing in the STB-3 laboratory within the next month.

4.2. Three-Phase Approach

The phased approach of STB-3 has been alluded to at several points. This approach was selected for two major reasons. The first is that it separates two difficult problems, so that we can address each individually. The first problem, which has never been done before, is just building a three-baseline interferometer (and pseudostar, which arguably may be the more difficult task) and demonstrating that the pathlength feedforward technique works. The second problem is operating it all on a flexible structure, which will introduce cross-coupling and plenty of other difficulties.

The second reason is that the phased approach allows the development of the long-lead structure while the Phase 1 hardware and software is being integrated and tested. Initial PFF testing in the low-frequency regime can be done on optical tables, thus relaxing the schedule for the structure.

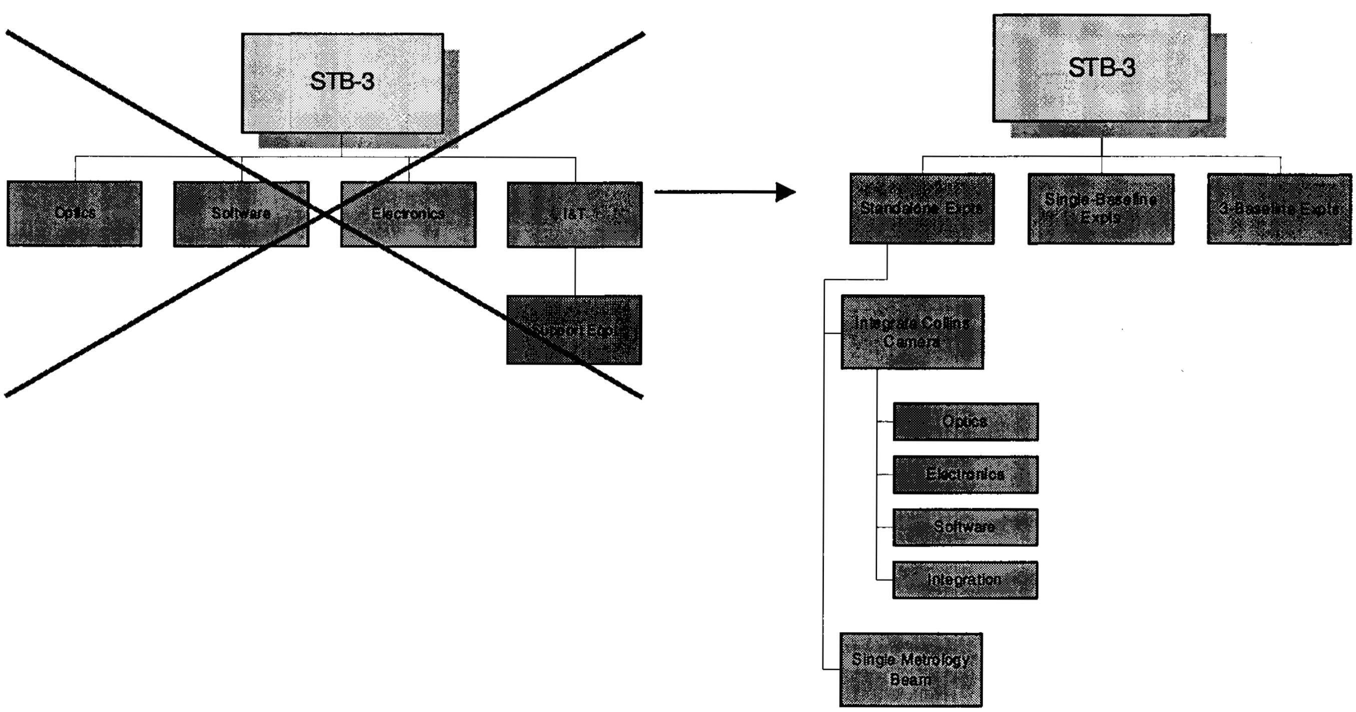
A second fortuitous effect of this approach is that the development of the complex external metrology system can also be parallelized. Since the system is on optical tables, all the motions that it goes through for which PFF corrections must be applied are rigid-body modes, for which the external metrology system would just report zero relative baseline motion. The external metrology system, with its complex and numerous (18) beams and high-powered lasers and safety issues, can be separately developed in another facility in parallel with the initial PFF performance testing of the Phase 1 hardware.

4.2.4. The Structure

The structure has been shown earlier. It is an aluminum panel structure, with significant cutouts. The purpose of the cutouts is to make the structure transparent to acoustic inputs.

4.3. Management Approach

The management of a technology testbed like STB-3 calls for different approaches from the management of the development of a product whose behavior is more predictable. Particularly, the interdisciplinary nature of interferometry exposes problems with traditional discipline-oriented work and product breakdown structures. In interferometers, the integration of a bunch of working components rarely results in a working system. For this reason, we take an approach to management of the task that is perhaps the dual of the traditional approach, shown here and explained in more detail below.



An additional item that must be factored heavily into the management approach is the integration of teams from three separate organizations, JPL, TRW, and Lockheed Martin, in a way that ensures success.

4.3.5. Work Breakdown Approach

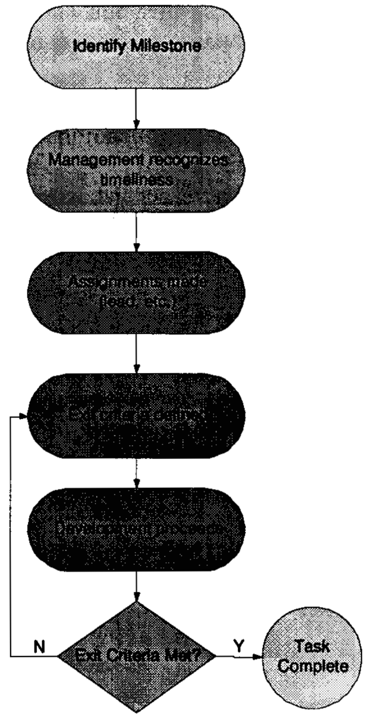
The STB-3 Work Breakdown Structure is based on demonstrable milestones of full-system functionality. That is, the work breakdown is vertical, not functional, as shown in the figure. Particularly noteworthy in this approach is that there is no Integration and Test (I&T) activity separately called out. Rather, the I&T function is built into each individual functionality milestone along the way, ensuring proper operation of each function in the context of the entire system.

Figure . STB-3 Work Breakdown Example

The team is small and special attention has been paid to selecting versatile people who can rapidly redeploy across functional lines. Everyone on the team takes ownership of system-level milestones.

This approach requires that management have significant vision into daily activities, so that people can be rapidly deployed to problem areas, and so that staff crunches can be avoided.

Finally, most critical to this approach, management must identify crisp, meaningful, and appropriate milestones, with clearly articulated exit criteria. The exit criteria for each task are key, as success is jeopardized if these do not accurately reflect the input criteria for follow-on tasks. This process is illustrated in the figure at right.



The tables below illustrate how team members are deployed to tasks rather than disciplines, with each team member possibly responsible, or jointly responsible, for more than one discipline within the scope of an individual task.

Delay Line Tracking	*Lead*	*Metrology*	*Optics*	*Electronics*	*Software*	*Controls*
Goullioud		X	X			
Azizi		X	X			
Graves				X		
McCreary					X	
Hench						X
Hendrix				X		
Irwin	X			X	X	

Single Metrology Beam	*Lead*	*Metrology*	*Optics*	*Electronics*	*Software*
Goullioud	X	X	X		
Azizi		X	X		
Graves				X	
McCreary					X
Irwin				X	

4.3.6. Partnering Approach

Within STB-3, industry roles have been defined as follows. JPL has management leadership and responsibility for technical oversight, and most of the day-to-day operations and development of the testbed.

TRW is responsible for the development, integration, testing, and modeling of the STB-3 structure, a task that amounts to about $1.5M mostly over the course of one year. TRW also provided mechanical and structural design support for the Phase 1 testbed. This falls nicely in line with TRW's role as the spacecraft systems vendor and final mission integrator for the SIM mission.

Lockheed Martin provides architectural co-leadership with JPL, and takes the lead in systems engineering and analysis and participates heavily during system testing and integration. This is aligned with Lockheed's role as the vendor of the interferometer instrument for SIM, and as the team which will perform the final instrument integration and test for SIM.

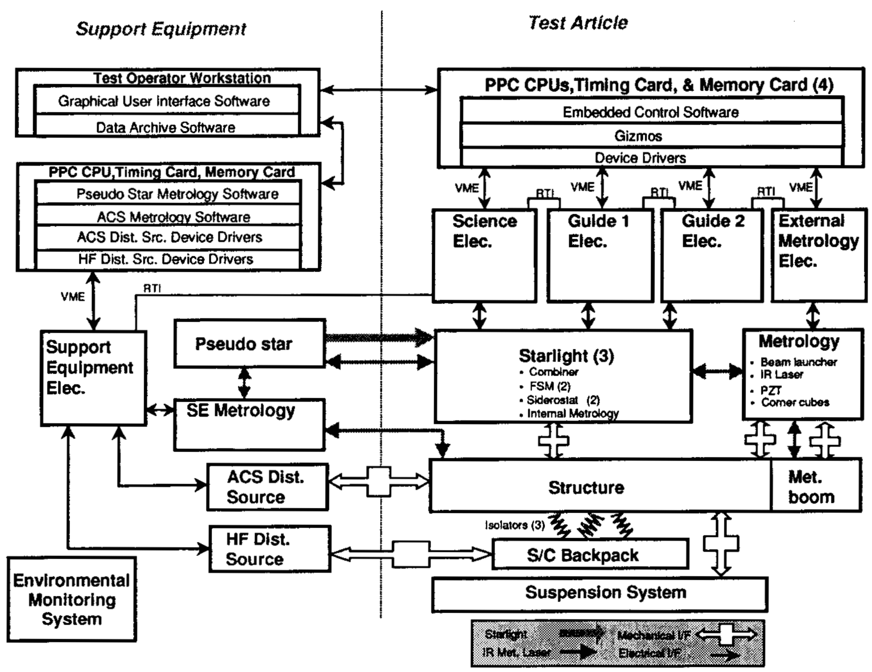
4.3.7. Budget/Cost Plan

The spreadsheet below shows the cost for each of the contractors' efforts over the three years of the project. (*) Note that in FY99, while both TRW and Lockheed participated in the project, all accounting was through a single JPL number, so the individual breakouts are not available.

	Raw JPL Cost			
Org	FY99	FY00	FY01	Totals
JPL	2,985.0*	3,327.5	2,269.8	8,582.3
LM	*	524.4	646.1	1,170.5
TRW	*	1,384.0	67.0	1,451.0
Totals	2,985.0	5,235.9	2,982.9	11,203.8

5. STB-3 DESIGN

This diagram illustrates the components that make up the STB-3 testbed, from a system-control point of view. I will not elaborate here as most of these elements have been previously discussed in some form. Also, the STB-3 Optical Design is presented in another paper at this conference[1] and is not covered here.



6. CONCLUSION

STB-3 is designed as the technology article which looks most like SIM of all the ITP testbeds, and it is attacking the challenging problem of demonstrating stabilization of dim-star fringes using information fed forward from two bright guide interferometers, on a flexible structure. Significant work has been done to date, and performance data is expected to emerge from the testbed in the next 1-2 months. The testbed will move onto a flexible structure in late 2000, at which point the full scope of performance testing will occur.

ACKNOWLEDGEMENTS

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